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Bandwidth Limits and Other Considerations for Monostatic RCS Reduction by Virtual Shaping

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14. ABSTRACT
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15. SUBJECT TERMS
radar cross section (RCS) reduction, virtual shaping, bandwidth limits, reflectarrays, and microstrip patch antennas

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Abstract

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Introduction

The two main methods to reduce the radar cross section (RCS) of a target are shaping the target geometry to deflect the scattered radar beam away from the incident direction (for monostatic radars) and absorbing the incident radar beam in the target by using radar absorbing materials or structures (RAM/RAS). Limits to shaping are imposed by the physical constraints of aero- and hydro-dynamics (for aircraft and for ships) and of internal volume and stability requirements for the target platform. One possible way to circumvent these problems is to decouple the radar scattering pattern from the physical shape of the target by imposing a linear phase gradient on the target scattering elements; this gradient serves to deflect the main lobe of the scattered radar signal away from the radar receiver. Since absorption is per wavelength of the incident radiation, such a scheme may also be a useful alternative for the absorption of low frequency radar waves, which can require rather thick and heavy layers of materials. The technique of causing the radar-apparent shape and orientation of an object to differ from its actual physical shape and orientation by imposing a phase gradient on the reflection from the target surface will be referred to as virtual shaping.

A practical way to produce a desired phase gradient on a surface (flat or conformal to a curved surface) is to use a reflectarray composed of an array of microstrip patches [1-3]. Reflectarrays combine the properties and advantages of reflectors and of phased array antennas. Microstrip antennas are very thin conducting patches lying on a conductor-backed dielectric substrate that are fed by a coaxial probe through the substrate. Such a patch can also be excited by an aperture coupling a waveguide into the substrate or by a microstrip transmission line on the substrate surface that connects to the microstrip patch. A reflectarray is a flat or conformal array of microstrip patches, with no feed lines or aperture coupling, on a thin conductor-backed

dielectric substrate that is illuminated by a microwave horn antenna or other source some distance above the array. Each patch of the array scatters the feed radiation with a different phase so that the resulting array scattering is at a different angle than that of specular reflection and the far field appears to have been reflected from a spherical or parabolic curved reflector. The concept of a reflectarray is shown in Figure 1 (taken from Reference 3). Radiation from the feed horn is incident on the array, where each of the elements reflects this radiation with a different phase that is determined by the phase shifters. The geometry of a microstrip reflectarray is shown in Figure 2 (taken from Reference 8). The phases are chosen in this case so that the reflected signal is a plane wave traveling in direction $\mathbf{r}_0$. The phase of the reflection coefficient for radiation normally incident on a periodic array of square patches vs. patch size for the three frequencies 11.5, 12.0, and 12.5 GHz is shown in Figure 3; it has a maximum range less than 360°. The phase shifts at the same frequencies for a two layer and for a three layer periodic array are shown in Figure 4; Figures 3 and 4 are taken from Reference 13. The additional layers increase the maximum range of the phase shift and smooth the dependence of the phase variation on patch size. This helps to increase the bandwidth of the reflectarray. As the source antenna feed recedes from the array, the system eventually comes to resemble that for monostatic RCS reduction for an incident plane wave by reflected beam deflection through virtual shaping of the reflectarray surface.

Application of Reflectarrays to Virtual Shaping

Both microstrip antennas and reflectarrays have several desirable features, such as low weight, small size, and low profile (so they can be made conformal to an arbitrary surface), and are thus quite rugged. They also have low cost of design and of manufacture. Both also have the major disadvantage of a very narrow bandwidth, typically a few percent of the operating frequency. Their broadside radiation pattern can also possess high sidelobes. For many applications, a wider bandwidth is required; in particular, this is true for RCS reduction by virtual shaping of a surface by a reflectarray of microstrip patches such as in the S-band of 2 – 4 GHz. For radar applications there are several related difficulties that must be overcome. These include not only increasing the bandwidth for useful beam deflection, but also (1) reducing the sidelobes below some specified level, (2) minimizing the reflection from the exposed dielectric area of the surface, and (3) performing these functions at an affordable cost. These will be addressed in turn, starting with the major problem of increased bandwidth.

Bandwidth

There has been a great deal of effort to widen the operational bandwidth of microstrip antennas. All the methods used have tried to overcome the fundamental bandwidth limitation set by the small electrical volume occupied by the microstrip elements [4]. Another way to express this is to realize that a microstrip patch antenna is a resonant structure, usually with high Q [5], that is, the ratio of electromagnetic energy stored in the vicinity of the patch to the electromagnetic energy radiated or scattered (or otherwise dissipated) by the patch per cycle is very large. The three main approaches to producing microstrip antennas with improved impedance bandwidth are [6]:

1) Use of an increased antenna volume, either by increasing the area or by stacking, such as by parasitic elements, overlay techniques, stepped substrates, or an annular ring

2) Use of matching techniques, such as employing multiple resonance effects or using the feed probe as a matching device

3) Use of elements with high internal losses, such as patch spirals or curved sections.

As there is a strong correspondence between the volume occupied by a microstrip element and its impedance bandwidth, utilization of the maximum volume available is a first step in conformal (or planar) antenna design [6].

Since a reflectarray is merely a reflecting device, not a radiating antenna, there is no need for any current injection. This eliminates one of the major causes of narrow bandwidth, but also precludes widening the bandwidth by the use of parasitic elements or by using the feed probe as a matching device. A common problem with increasing antenna volume by using a thicker substrate is the increased surface wave loss for high permittivity substrates and greater feed probe losses for low permittivity substrates [4]. As the substrate thickness increases the resonant frequency decreases, so that the frequency bandwidth around the resonant frequency increases [7,8].

Each microstrip patch element of the reflectarray imparts a different phase to the field it scatters. For monostatic RCS reduction, a plane wave incident within some range of angles to the normal of the array surface must be deflected through an angle different than that of specular reflection and large enough to avoid being backscattered to the radar transmitter/receiver. A quantitative statement of this requirement is that an S-band plane wave incident at any angle θ_i in the range $-\theta_M < \theta_i < +\theta_M$, i.e., that $\theta_i \in \Omega_M$, be reflected outside this range, so that the reflected angle (no longer equal to the specular reflection angle θ_s) $\theta_r \notin \Omega_M$. The reflected field phase vs. patch length for an infinite array of microstrip patches with plane waves incident at various angles is shown in Figure 5 (taken from Reference 39). To be specific, let a wave incident at $\theta_i = +\theta_M$ be reflected at the angle $\theta_r = \theta_M + \Delta\theta$, where $\Delta\theta$ is large enough to deflect the main reflected lobe outside of Ω_M. Since the specular reflection angle for this extreme case is $\theta_s = -\theta_i = -\theta_M$, the phase gradient must deflect the reflection through an angle $2\theta_M + \Delta\theta$. This sets the condition on the linear phase gradient of the array that will exist for all incident angles $\theta_i \in \Omega_M$, viz., $2\pi L/\lambda (\sin\theta_i + \sin\theta_r) + \Delta\phi = 0$ for the main lobe, where $\Delta\phi$ is the total relative phase shift difference over the entire reflectarray surface of extent L for wavelength λ of the radiation. For 3GHz radiation, $\lambda = 10$cm; for $L = 10$m, $\theta_M = 15°$, and $\Delta\theta = 5°$, $\theta_r = \theta_M + \Delta\theta = 20°$ and $\Delta\phi = 2\pi \times 60.1$, which is many tens of times a 2π phase change. Hence, either a very thick multilayer of patches or a set of subarrays, each with a 2π (or small multiple thereof) maximum relative phase difference, is required to produce the necessary phase difference. Such a multilayer may be physically too thick to be practical, while an assembly of such subarrays produces a much wider main lobe scattering pattern. The width of the subarrays in terms of relative phase shift may not be, at least approximately, constant for all frequencies of interest, which can drastically alter the scattering pattern for the entire array. The same phase difference will exist for all other incident angles. In particular, for a normally incident wave ($\theta_i = 0$), the reflected wave will be

approximately at angle $\theta_r = 2\theta_M + \Delta\theta = 35°$; similarly, a wave incident at $\theta_i = -\theta_M$ will be reflected at approximately $\theta_r = 3\theta_M + \Delta\theta = 50°$.

One method to control this reflection phase is to attach a stub, of various lengths, to each microstrip patch, as is shown in Figure 6 (taken from Reference 3). A better method is to use patches of various sizes to construct the array, as shown in Figure 7 (taken from Reference 13). Both methods introduce a small phase shift in the resonant frequency of the element, which produces a change in the phase of the scattered field [8]. The use of patches of variable size has several advantages over the use of stub-tuned patches, such as a wider bandwidth, much smaller cross polarization, and no need for surface space devoted to the stubs [9,10].

The bandwidth of a microstrip reflectarray is limited primarily by two factors, the narrow bandwidth of the microstrip element itself and the differential delay of the array [11]. This latter concept is shown in Figure 8 (taken from Reference 11). For any particular incidence angle, the $1/\lambda$ ($\sim \omega$) dependence means that the relative phase difference of the incident wave is frequency dependent [12]. For RCS reduction problems, this latter limit on the bandwidth is related to the aperture fill time, the time $(L/c) \sin\theta_i$ required for a plane wave incident at angle θ_i to illuminate or to fill the entire aperture of extent L. A wider bandwidth can be obtained by using a thick substrate for the patch, by stacking multiple patches, and by using sequentially rotated subarray elements [11]. The use of multiple layers of patches allows the phase of the reflected wave to vary over a range greater (or even much greater) than 2π and provides a smoother dependence on patch size [13,14]. Examples of two- and three-layer reflectarrays are shown in Figure 9 (taken from Reference 13) and Figure 10 (taken from Reference14). Computation for analyzing scattering by multilayered periodic structures has also been treated [15], as has analysis of stacked microstrip patches [16].

Another possible solution to the bandwidth problem is the use of a fractal reflectarray, that is, an array whose elements are distributed in a fractal pattern. A fractal is an object with dilation/translation invariance (self similarity) of some sort; it can be considered to have structure at all (or for a wide range of) length scales [17,18]. Since the fractal pattern is self similar, it produces a self similar scattering pattern; for every change in wavelength that equals the scale of self similarity, the scattering pattern will be the same except for a widening of the scattering lobe structure due to the finite size of the fractal object, and for the effects of dispersion of the dielectric permittivity.

Since a narrow bandwidth is such a severe constraint, especially for RCS applications of microstrip reflectarray devices, the first order of business is to determine, or at least to estimate, the maximum possible bandwidth range for which such a device can reduce by a specified amount the RCS of a ship structure. There are several related topics in various areas of physics that are relevant to the determination of this limit. These include causality conditions [19-23], time delay [24-26], dwell time [27], and partial wave phase shifts [28-30]. By causality condition is meant that there can be no scattered wave before the incident wave reaches the scatterer [22]. A different form of this condition is given by van Kampen [21], who requires that the total probability outside the scatterer never exceed its initial value; he also [20] considers the scattering of photons by a spherically symmetric scatterer outside of which the interaction is exactly zero. Gell-Mann *et al.* [23] are more stringent in that they require not only that waves

cannot be scattered before the incident wave arrives, but also that even after the arrival one must wait the appropriate time to receive a signal. Their causality requirement is the quantum mechanical formulation of the condition that waves do not propagate faster than the velocity of light.

The concept of time delay in scattering was introduced by Eisenbud and Wigner [28]. Nonrelativistic quantum *s*-wave scattering produces a phase shift $\eta(E)$ at energy E; the time delay is given by $\Delta t = 2(h/2\pi)\, d\eta/dE$, where h is Planck's constant. For a plane-wave packet incident on a spherically symmetric scatterer that produces scattering amplitude $f(E,\theta)$ in the direction θ, the time delay in this direction is given by [31] $\Delta t = 2(h/2\pi)\, \partial[\arg f(E,\theta)]/\partial E$. The different definitions or interpretations of the delay time are discussed by Nussenzveig [24]. He goes on to extend his previous work [25] to find the average time delay in electromagnetic scattering by a spherically symmetric, reflection-invariant, non-absorbing scatterer. For the *l*th partial wave in each polarization the time delay is the spectral average of $d\eta_l/d\omega$ over the incident wave packet, where η_l is the corresponding phase shift and ω the angular frequency. A review of time delay and related concepts, including their many applications in physics, is given by Carvalho and Nussenzveig [26].

For many of the problems treated in these references, spherical symmetry of the scatterer or of the scattering potential allows a straightforward partial wave expansion of the scattered field. For the reflectarray problems of interest here, it may be better to use a plane wave angular spectrum expansion for the scattered waves [32,33]. There is still a scatterer of finite extent, but it is no longer spherical. The reflectarray can be confined to a finite region that is bounded by $z = 0$ to $z = h$ in the z-direction (normal to the reflectarray surface) and by $|x| < a$, $|y| < b$ (or $\rho = |x^2 + y^2|^{1/2} < P = (a^2 + b^2)^{1/2}$) in the transverse directions x and y. An increase in the thickness z of the reflectarray can increase the bandwidth (recall Figures 3 and 4 for normal incidence), while an increase in the transverse dimension can decrease the bandwidth for all but normally incident radiation (due to the differential spatial phase delay [11,12]).

Sidelobes

Low sidelobes for antennas have been of interest for clutter rejection. They are also a good counter to ECM (electronic countermeasures), such as jamming [34]. The two parts to designing a low sidelobe antenna are (1) to choose the correct illumination function to obtain the desired design (error-free) sidelobes, and (2) to control the phase and amplitude errors that produce the random sidelobes, which fundamentally limits sidelobe performance [34]. The illumination function is defined and limited only by the allowed range of the incidence angles, $\theta_i \in \Omega_M$, so it cannot be completely known. Purely random errors produce random sidelobes, while correlated random errors produce sidelobe energy that is concentrated at discrete locations in the far field; this gives rise to higher sidelobes in a limited number of locations [35]. The factors influencing the realizable sidelobe performance of a microstrip antenna array are discussed by Pozar and Kaufman [36]. It should also be noted that they conclude their paper with the comment [36]: "Finally, it might be noted that this work represents a good example of how theoretical analyses, on which most of the results in this paper are based, can be applied to a practical but difficult problem in antenna engineering that would probably remain unsolved if attacked with purely empirical techniques."

The use of a fractal array can also aid in the suppression of sidelobes. Kim and Jaggard [37] describe the advantages of a fractal array: "While random arrays are robust with respect to element location errors and failures they are characterized by relatively high sidelobes. Uniform or tapered periodic arrays possess relatively low sidelobes but are sensitive to errors in location and to the values of the excitation currents. Here the virtues of random and periodic arrays are combined by interjecting self similarity into random array theory to control the sidelobe radiation pattern." For example, an infinite Cantor array has the same array factor at an infinite number of bands (it is a multiband system, not a frequency-independent system); its behavior will be the same at several bands, but will not be frequency-independent within each band [38]. A band-limited realization of such a fractal structure will have similarity properties through as many bands as iterations used in the construction of the array [38]. As the frequency of the radiation is reduced (so its wavelength is increased), the width of the main scattering lobe will increase. The secondary lobes of the scattering pattern will also be high; this feature is related to the array characteristic known as lacunarity. A fractal structure possesses high lacunarity when it has large gaps between the different fractal substructures [38].

Lacunarity/Reflection From Exposed Dielectric Surface Area

The spatial scale of a fractal reflectarray is set by the frequency range over which it is to operate. The highest operating frequency determines the size of the smallest elements through their resonant frequency. The size of the array and its operational bandwidth determine the number of iterations of the generating pattern. For a fractal array of microstrip patches on a conductor-backed dielectric sheet or substrate, high lacunarity can also produce at the higher operating frequencies significant specular reflection from the large area of bare dielectric surface between the conducting patches. Radiation incident on this bare dielectric will be reflected from the bare surface or will enter the substrate and will then be reflected from the conducting ground plane. In both cases there will be specular reflection that must be reduced in intensity. If the specularly reflected field is included in the analysis [9] of an infinite array of microstrip patches, then at the design frequency of the reflectarray the scattered field from the patches is of nearly equal amplitude and has an approximate phase difference of 180 degrees compared to the specularly reflected field; this effectively eliminates the specular reflection [39] and may be useful for the problems considered here. The RCS of a patch on an isotropic substrate has been calculated and compared to measurements [40]. One possible way to address the problem of scattering from a large surface area of bare dielectric is to use a series of multilayers arranged in such a way that they form a thick slab of a "three"- rather than just a "two"-dimensional fractal object. For example, a Cantor bar fractal array could be placed at a right angle to another such array above (or below) it to reduce the amount of bare dielectric. Similarly, a series of layers based on the Sierpinski carpet can be arranged to form a slab of a "three"-dimensional fractal, somewhat like the Menger sponge [17]. One way to achieve this is to displace each layer of microstrips with respect to its neighboring layers.

Cost

The technology for microstrip antennas and reflectarrays has existed for several decades; construction methods are well known, and one of the major advantages of this technology is its

low cost both for design and for construction [4]. The techniques to construct actual devices that realize virtual shaping, as well as the costs of so doing, are thus known quantities. The use of different- sized patches to vary the phase of the field reflected from each element is more economical than the use of tuning stubs, shorting walls, shorting pins, or patch components perpendicular to the substrate surface [41].

Conclusion

The major obstacle to the use of microstrip patch and reflectarray technology for RCS reduction is their narrow operational bandwidth. To be useful for naval applications the bandwidth must be greatly expanded. Some of the continuing efforts recounted here have produced modest increases. Some possible methods to address the bandwidth, sidelobe, and exposed dielectric reflection problems have also been discussed here. One of the first goals is at least to estimate, if not determine precisely, any fundamental limits on the bandwidth of the reflectarray approach to virtual shaping. If such bandwidth limits to problems of interest to the navy are weak, the goal shifts to achieving performance for RCS reduction in the presence of sidelobes and other scattered signal phenomenon for the required bandwidth in an economical manner.

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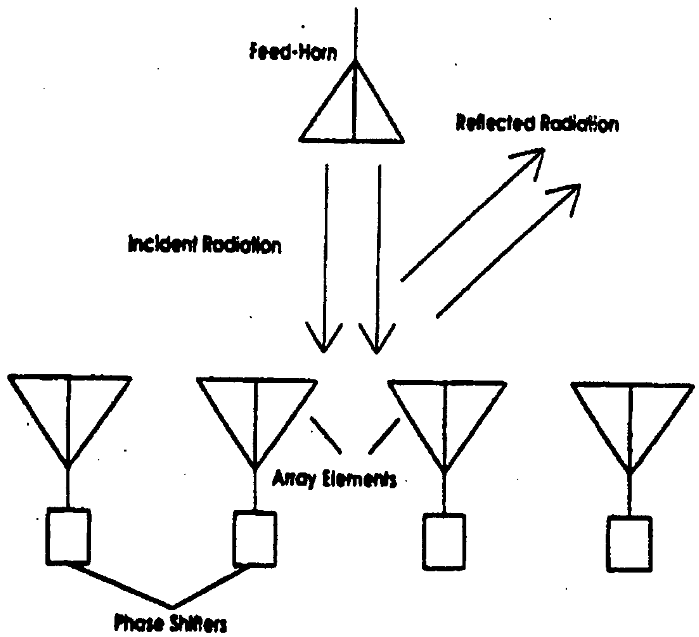

Figure 1. Reflectarray concept. From R.D. Javor, X-D. Wu, and K. Chang, IEEE Trans. AP43(9) pp. 932-939, September 1995

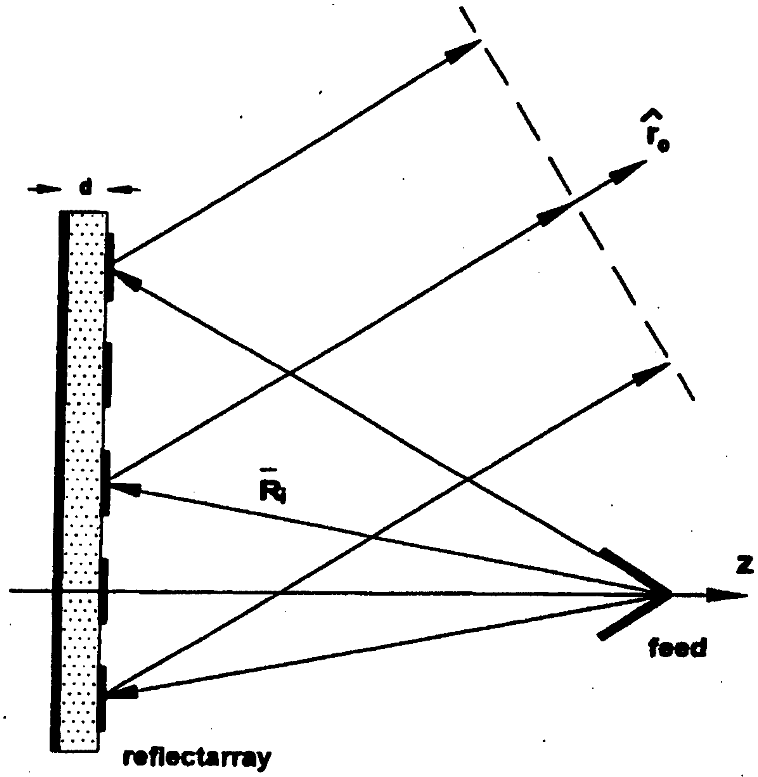

Figure 2. Geometry of the microstrip reflectarray. From D.M. Pozar, S.D. Targonski, and H.D. Syrigos, IEEE Trans. AP45(2), pp. 287-296, February 1997

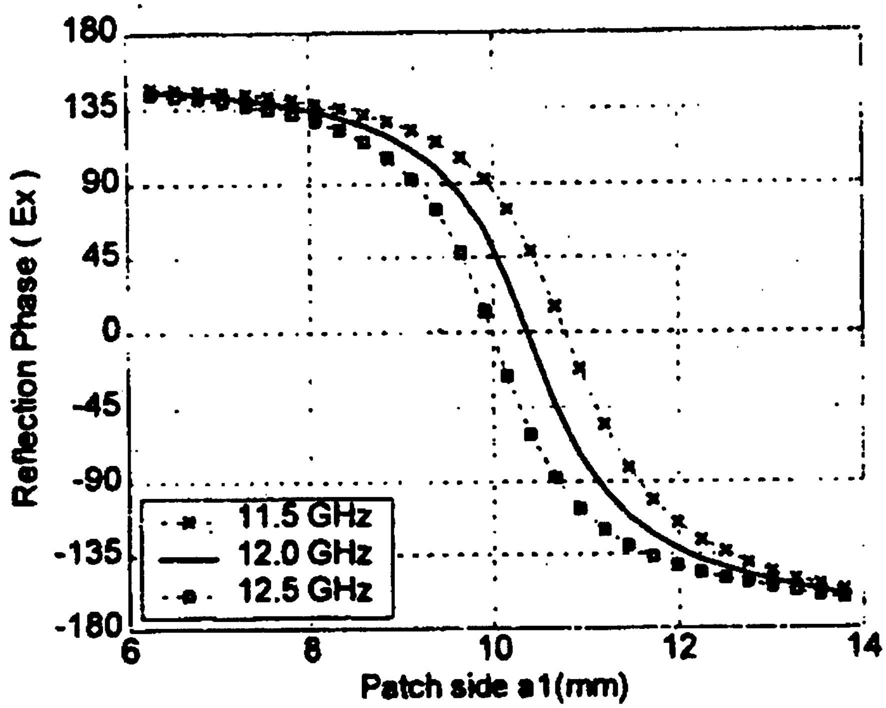

Figure 3. Phase of reflection coefficient at normal incidence for a periodic array of square patches on a grounded substrate versus the patch side a_1 at three frequencies (a = 14 mm, h = 1 mm, ε_r = 1.05). From J.A. Encinar, IEEE Trans. AP49(10) pp. 1403-1410, October 2001.

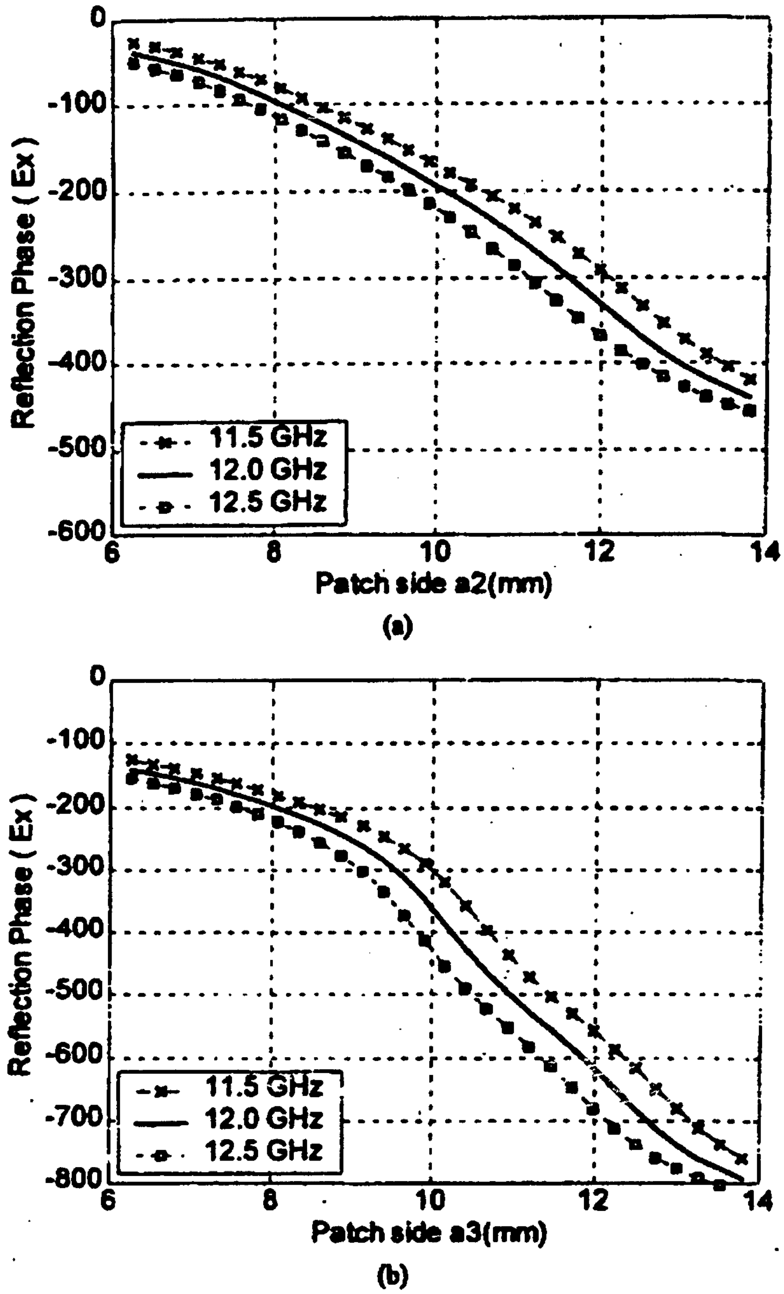

Figure 4. Phase of reflection coefficient at normal incidence for a multilayer periodic structure, defined in Figure 9(c) for two layers, versus the patch side of the array closer to the ground plane. ($a_1 = b_1$, $a_2 = b_2$, a = b = 14 mm, $h_1 = h_2 = 3$ mm, $\varepsilon_r = 1.05$). (a) Two array layers ($a_1 = 0.7a_2$). (b) Three array layers ($a_1 = 0.7a_3$, $a_2 = 0.9a_3$). From J.A. Encinar, IEEE Trans. AP49(10) pp. 1403-1410, October 2001

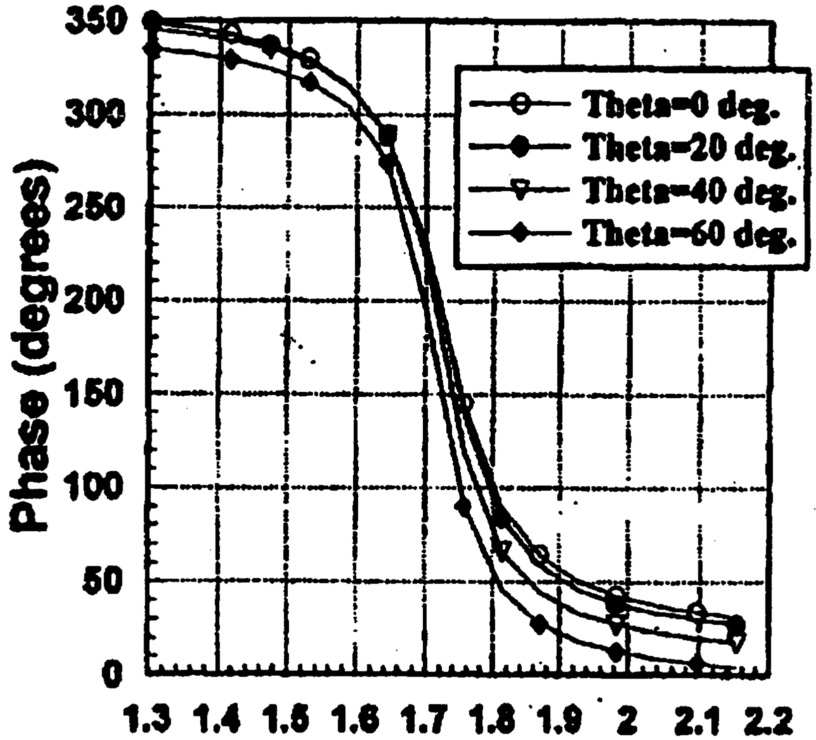

Figure 5. Reflected field phase versus patch length for an infinite array of microstrip patches with plane wave incidence at various angles. From S.D. Targonski and D.M. Pozar, IEEE Int. Symp. AP, Seattle, WA, pp. 1820-1823, June 1994.

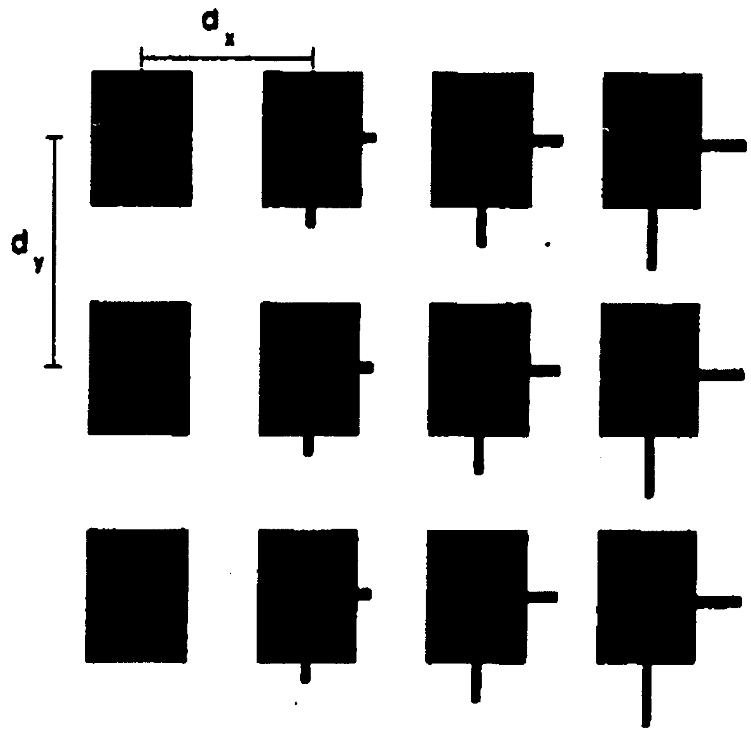

Figure 6. Dual-polarized array. From R.D. Javor, X-D. Wu, and K. Chang, IEEE Trans. AP43(9) pp. 932-939, September 1995

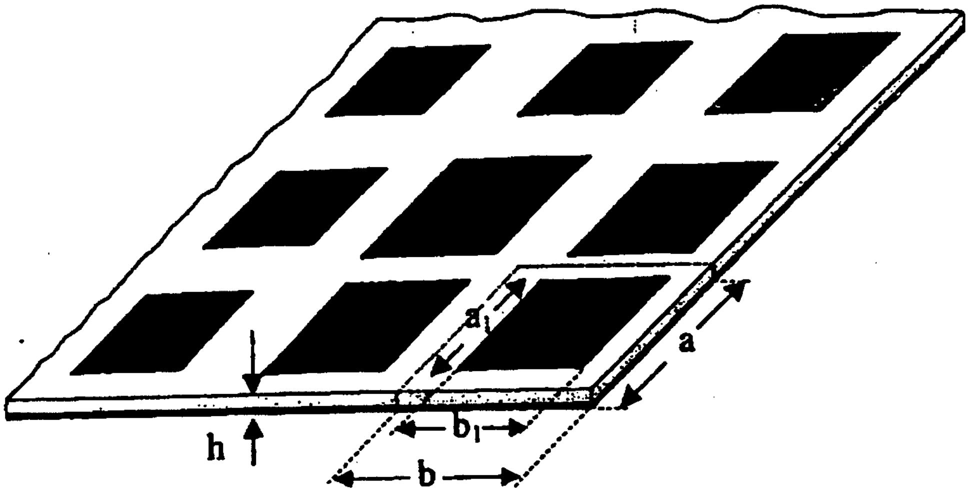

Figure 7. Microstrip reflectarray with rectangular patches of variable size to control the phase. From J.A. Encinar, IEEE Trans. AP49(10) pp. 1403-1410, October 2001

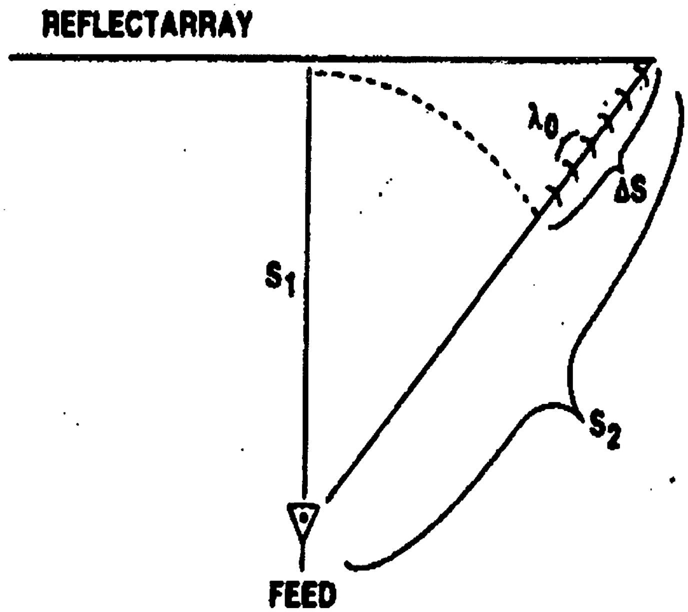

Figure 8 Differential spatial phase delay of reflectarray. From J. Huang, IEEE Int. Symp. AP, Newport Beach CA, pp. 582-585, June 1995

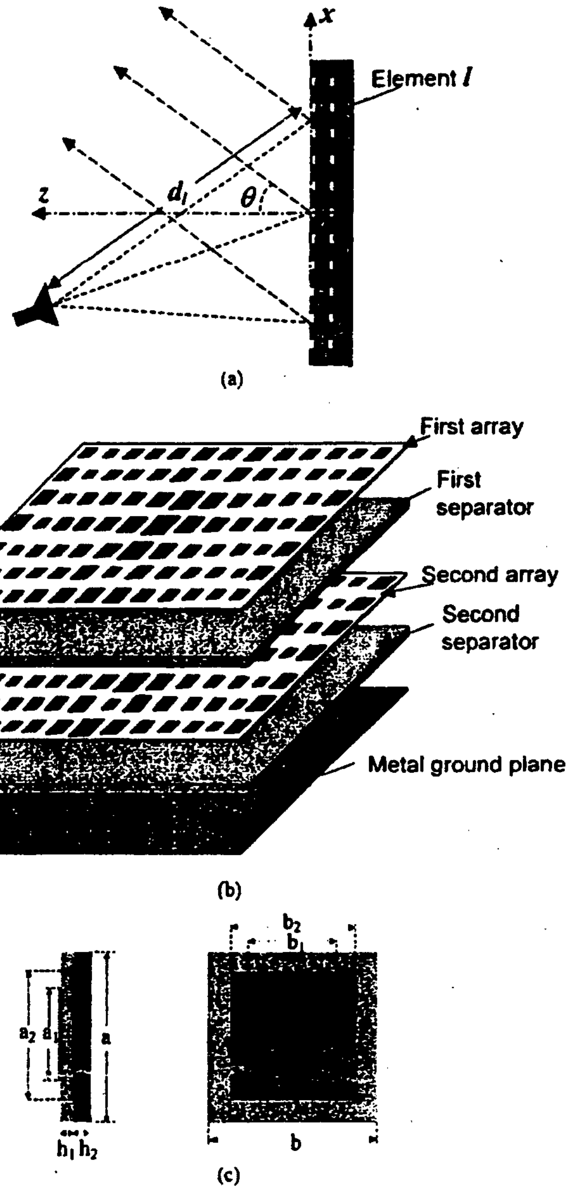

Figure 9. Two-layer reflectarray using patches of variable size. (a) Reflectarray illuminated by a feed. (b) Multilayer structure. (c) Periodic cell. From J.A. Encinar, IEEE Trans. AP49(10), pp. 1403-1410, October 2001.

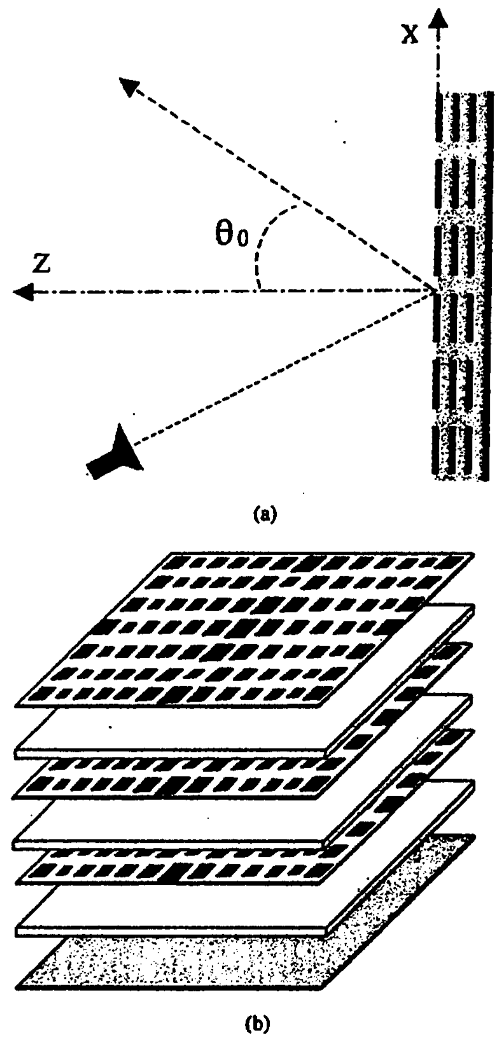

Figure 10 Three-layer reflectarray using patches of variable size. (a) Reflectarray illuminated by a feed. (b) Multilayer structure. From J.A. Encinar and J.A. Zornoza, IEEE Trans. AP51(7), pp. 1662-1664, July 2003.

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